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A suite of novel high-resolution spectroscopic imaging diagnostics have facilitated the identification and localization of molybdenum impurities as the main species during the formation and lifetime of impurity-induced snakes on Alcator C-Mod. Such measurements made it possible to infer, for the first time, the perturbed radiated power density profiles from which the impurity density can be deduced.

I. INTRODUCTION

Understanding the formation and stability of 3D helical modes in the core of an otherwise, axisymmetric toroidal configuration, is one of the challenges of current fusion research. An example of such 3D helical perturbations is the long-lived \((m, n) = (1, 1)\) mode first found at the Joint European Torus\(^1,2\) right after the injection of a high-speed frozen deuterium pellet. The typical snake-like helical patterns observed (e.g. see Figure 1) are characterized by a small region of localized and enhanced plasma density that rotates within the field of view of the soft x-ray (SXR) arrays and is radially concentrated on, or inside the \(q = 1\) surface. The formation of these phenomena have been generally attributed to the local cooling of flux surfaces caused by the intersecting trajectory of the fueling pellet, which is strongest at the \(q = 1\) rational surface where just a single field line transit leads to a rejoining of the field line\(^3\).

Snakes have been a common feature in every major tokamak fusion experiment, including spherical tori and reversed field pinches. A second type of snakes like the one depicted in Fig. 1, produced by an accumulation of heavy-impurity ions rather than the deuterium ions from injected fueling pellets, is also observed. Both types of snakes possess surprisingly good MHD stability and particle confinement, since they can survive tens to hundreds of sawtooth cycles. This paper reports new experimental data on the heavy impurity snakes in the Alcator C-Mod experiment\(^4\), which leads to a new picture of its formation and sustainment; the results and their interpretation may also shed light on the formation and stability of pellet-induced snakes.

A suite of novel spectroscopic imaging diagnostics has facilitated the identification of the major impurity ion species and the determination of the perturbed radiated power inside the \(q \leq 1\) region with unprecedented temporal and spatial resolution. Such measurements have enabled - for the first time - estimates of the impurity density, toroidal plasma flow velocity, \(Z_{\text{eff}}\), and resistivity of the \(n = 1\) helical structure.

II. X-RAY CRYSTAL IMAGING SPECTROMETER DETECTS MOLYBDENUM EMISSION

The identification of the main impurity species was possible using the High Resolution X-ray crystal imaging spectrometer with Spatial resolution (HiReX-Sr)\(^5,6\). Although this diagnostic was designed primarily for extracting temporally and spatially-resolved spectra from argon, it is also possible to monitor intrinsic impurities such as molybdenum; the latter is the main high-\(Z\) intrinsic impurity at C-Mod since more than 95% of the plasma facing components are made out of pure molybdenum and/or TZM, an alloy that contains 99% Mo, 0.5% Ti and 0.08% Zr. The average molybdenum ion charge for a core electron temperature of interest \((T_{e,0} \sim 1 – 3 \, \text{keV})\) is \(\langle Z_{Mo}\rangle = 32\), with a broad ion fraction of \(\sim 50\%\) for \(Z = 32\), and \(20\%\) and \(30\%\) for \(Mo^{31+}\) and \(Mo^{33+}\), respectively\(^7,8\). Spatially resolved molybdenum spectra obtained at four different times are shown in Figure 2 and clearly indicates that the molybdenum emission tends to increase from \(t = 0.2\) s to \(t = 0.334\) s before the \(m = 1\) snake is formed. A time-dependent multi-gaussian non-linear least-squares fit was applied to the binned data obtaining the peak amplitude, as well as Doppler widths and shifts for each of the emission lines\(^5,6\). The intensity of the line-integrated \(Mo^{32+}\) brightness profiles - obtained
with a reduced integration time of 10 ms - are shown in Figure 3-a), and indicate a slow peaking of molybdenum density before the snake formation. The flat core brightness profile obtained after the snake is formed [see brown trace in Fig. 3-a] for $t \sim 0.334 \text{ s}$ is an integration artifact since the spectrometer acquisition time is much larger than the transit time of the snake around the torus ($\sim 0.2 \text{ ms}$). The normalized intensity of the central Mo$^{32+}$ brightness is over-plotted in Fig. 3-b), and shows a remarkable agreement with the normalized central soft x-ray (SXR) brightness signatures from the tomographic array. It is thus safe to assume that the net core emission in the time-interval $t \in [0.2, 0.5]$, is strictly due to the presence of molybdenum charge states, and that the snake-like pattern in the SXR data is formed by a small region of localized and enhanced molybdenum density on, or inside the $q = 1$ surface.

III. SXR TOMOGRAPHY OF SNAKES

The C-Mod snake formation can be described by a multi-step process which is here illustrated using the 2D SXR tomographic reconstructions shown in Fig. 4. These reconstructions were obtained using as a basis of fifteen radial (Bessel) harmonic numbers, a singular value decomposition (SVD) tolerance value of 0.1, a 48 and 84 cm horizontal and vertical emissivity grid with a spatial resolution of 1 cm, and a time step of 4 ms; more information on the mathematics of this tomographic inversion capability can be found in references $^9, ^{10}$. The initial plasma conditions are characterized by a high edge temperature which increases the molybdenum erosion from the inner wall, while the absence of sawteeth crashes results in on-axis impurity peaking; this impurity accumulation in the core results in a peaked SXR emissivity profiles, as shown in Fig. 4-a). The inadvertent Mo injection at $t \sim 0.324 \text{ s}$ increases the peaking of the core SXR emissivity by $\sim 250 \text{ kW/m}^2$, but with a profile which is displaced radially outwards by approximately 1 cm from the original magnetic axis. The next phase is characterized by a displaced circular core that resembles now that of a low amplitude internal and ideal $(m,n) = (1,1)$ kink rotating with the plasma toroidal flow velocity. When the kinked-snake is first formed, the SXR emissivity increases an additional $\sim 5 - 10\%$ since most of the impurity emission is now restricted to a smaller volume element. The spatial extent of this kink-like structure grows in time during its first 2 ms before the first sawtooth-crash is observed.

The shape of the snake perturbation during its fourth phase resembles that of a $(1,1)$ internal resistive kink...
FIG. 5. (Color online) Radiated power density profiles a) before and b) right after the snake formation.

FIG. 6. (Color online) Radiated power density profile during the crescent-shape island phase.

with a magnetic island; the latter evolved from a wide D-shaped ideal kink to a radially narrower crescent-like island with a wider poloidal extent (compare Figs. 4-c and -d)]. The impurity accumulation at the center of the snake is such that its SXR emissivity is approximately four times bigger than that of the unperturbed core plasma, suggesting that the impurity density at the center of the snake is a few times larger than that of the background core.

IV. RADIATED POWER DENSITY MEASUREMENTS

An assessment of the radiated power density profiles before the snake formation - and throughout its lifetime (see Figs. 5 and 6) - was done using a high-resolution absolute XUV diode array\textsuperscript{11}. The peaked radiated power density profile before the snake formation is depicted in Fig. 5-a). If one considers a molybdenum cooling factor of $L_{\text{rad}} \sim 7 \times 10^{-32}$ W·m\textsuperscript{-3} for the core temperatures of interest, then the net core radiated power density of 3.1 MW/m\textsuperscript{3} will correspond to an electron and molybdenum density product $(n_{e,0}n_{\text{Mo},0} \Delta P_{\text{rad},0}^{	ext{Mo}})$ of $\sim 4.42 \times 10^{-67}$ m\textsuperscript{-6}, for a typical electron density of $1.5 \times 10^{20}$ m\textsuperscript{-3}, the molybdenum density and its concentration $(n_{\text{Mo},0}/n_{e,0})$ can be as high $3 \times 10^{17}$ m\textsuperscript{-3} and 0.2%, respectively. Such an impurity density can increase the core $Z_{\text{eff}}$, as well as the collision frequency and resistivity, by more than factors of two and three over the molybdenum-free state. The radiated power density measurements at the core during the kinked-snake, confirmed also the qualitative estimates obtained with the SXR tomographic system; the local emissivity increases an additional $\sim 5 - 10\%$ during the third-phase of the snake formation (see Fig. 5-b)]: in this case, the net radiated power densities from the background plasma and the snake are approximately 1.5 and 2.55 MW/m\textsuperscript{3}, respectively. The high signal-to-noise ratio enables fast emissivity reconstructions such that noticeable differences can be observed when the $m = 1$ island is at the outboard ($\theta = 0$) or inboard side ($\theta = \pi$). During the crescent-phase the radiated power density profiles decrease continuously since impurities are being flushed from the core by sawtooth crashes and the background transport. The example shown in Fig. 6 (for $t \sim 0.360$ ms, 20 ms after the snake formation) indicates that the net radiated power densities from the background plasma and the snake have decreased to 1.05 and 1.95 MW/m\textsuperscript{3}, respectively.

In summary, high-resolution diagnostic capabilities have facilitated the study of the role of radiated power density, impurity density, collisionality and resistivity on both the formation and saturation of these (1,1) snakes\textsuperscript{5,6,12}. Both the observation and its interpretation may shed light also on the formation of the snakes observed in fusion devices such as tokamaks, spherical tori and reversed field pinches. This work was performed under US DoE contracts DE-FC02-99ER54512 at MIT and DE-AC02-09CH11466 at PPPL.